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AMERICAN UNIVERSITY IN CAIRO

MASTER OF SCIENCE THESIS

Latency Optimization in Smart Meter Networks

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*A thesis submitted in partial fulfillment of the requirements
for the degree of Master of Science*

in Electronics and Communications Engineering

February 19, 2021

Declaration of Authorship

I, Amr Salah Kassab, declare that this thesis titled, “Latency Optimization in Smart Meter Networks” and the work presented in it are my own. I confirm that:

- This work was done wholly or mainly while in candidature for a research degree at this University.
- Where any part of this thesis has previously been submitted for a degree or any other qualification at this University or any other institution, this has been clearly stated.
- Where I have consulted the published work of others, this is always clearly attributed.
- Where I have quoted from the work of others, the source is always given. With the exception of such quotations, this thesis is entirely my own work.
- I have acknowledged all main sources of help.
- Where the thesis is based on work done by myself jointly with others, I have made clear exactly what was done by others and what I have contributed myself.

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Date:

AMERICAN UNIVERSITY IN CAIRO

Abstract

School of Sciences and Engineering

Electronics and Communications Engineering Department

Master of Science

Latency Optimization in Smart Meter Networks

by Amr Salah Kassab

In this thesis, we consider the problem of smart meter networks with data collection to a central point within acceptable delay and least consumed energy. In smart metering applications, transferring and collecting data within delay constraints is crucial. IoT devices are usually resource-constrained and need reliable and energy-efficient routing protocol. Furthermore, meters deployed in lossy networks often lead to packet loss and congestion. In smart grid communication, low latency and low energy consumption are usually the main system targets. Considering these constraints, we propose an enhancement in RPL to ensure link reliability and low latency. The proposed new additive composite metric is Delay-Aware RPL (DA-RPL). Moreover, we propose a repeaters' placement algorithm to meet the latency requirements. The performance of a realistic RF network is simulated and evaluated. On top of the routing solution, new asynchronous ordered transmission algorithms of UDP data packets are proposed to further enhance the overall network latency performance and mitigate the whole system congestion and interference.

Experimental results show that the performance of DA-RPL is promising in terms of end-to-end delay and energy consumption. Furthermore, the ordered asynchronous transmission of data packets resulted in significant latency reduction using just a single routing metric.

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List of Abbreviations

AMI	Advanced Metering Infrastructure
AODV	Ad hoc On demand Distance Vector
ARQ	Automatic Repeat Request
CFN	Common Forwarding Node
CFP	Contention Free Period
CSMA	Carrier Sense Multiple Access
DAO	Destination Advertisement Object
DCU	Data Concentrator Unit
DIO	DODAG Information Object
DIS	DODAG Information Solicitation
DODAG	Destination Oriented Directed Acyclic Graph
DSSS	Direct Sequence Spread Spectrum
ETX	Expected Transmission Count
LLN	Low power and Lossy Network
LTE	Long Term Evolution
LoRa	Long Range
MIMO	Multiple Input Multiple Output
MRHOF	Minimum Rank with Hysteresis Objective Function
MRM	Multi-path Ray tracer Medium
OF	Objective Function
OFDM	Orthogonal Frequency Division Multiplexing
OLSR	Optimized Link State Routing
PER	Packet Error Rate
PRIME	PoweRline Intelligent Metering Evolution
PSD	Power Spectral Density
RDC	Radio Duty Cycling

RPL	R outing P rotocol for L ow power and lossy networks (LLNs)
RSSI	R eceived S ignal S trength I ndicator
6LowPAN	I Pv 6 over L ow-power P rivate A rea N etwork
SM	S mart G rid
UDGM	U nit D esk G raph M edium
UDP	U ser D atagram P rotocol
Wi-MAX	W orldwide I nteroperability for M icrowave A ccess
Wi-SUN	W ireless S mart U tility N etwork
WM-BUS	W ireless M eter B US
WSN	W ireless S ensor N etwork

Chapter 1

Introduction

1.1 Smart meters network

Recently, there has been an increased interest in the field of the internet of things (IoT). One of the use cases of IoT is smart grid communications, and one of the essential elements of smart grid communication is the Advanced Metering Infrastructure (AMI). AMI consists of smart electric meters used to mainly monitor power consumption status and enable the collection of real-time measurements. The monitoring process necessitates sending useful information to a sink or aggregation node within an acceptable delay. In recent years, most smart metering networks have used more than one communication technology to achieve better system performance. Each of those has its own specifications and characteristics. While its low deployment cost characterizes the power line communication (PLC) technology, it is sensitive to interference and impulse noise that degrades the system reliability [1]. While the wireless radio frequency (RF) network may also suffer from noise and interference, it offers higher data rate transmissions but with lower reach-ability. Therefore, a hybrid RF and PLC network is recommended as a general solution to achieve more system reliability and extended coverage distances [2]. It is important for large realistic networks to dynamically enhance the network performance to meet the updated system constraints. Low Power and Lossy Networks (LLNs) [2], like wired PLC and wireless systems, aim to minimize the end-to-end delay and energy consumption. For a single-technology smart metering network, the

predefined requirements may be achieved by adopting and adapting current system architecture. Hence, network performance should be first simulated and evaluated sufficiently before the implementation and deployment process. This may also give a good insight for future integration with other wireless technologies. Routing protocol for low-power and lossy networks (RPL) seems to be the most common choice to enhance the performance of LLNs [3]. In [4], a new RPL objective function is introduced that simulates the battery consumption of nodes and hence aims to increase the network lifetime. The remaining energy of nodes is used in a large simulated network and evaluated in [5]. In [6], a new RPL additive metric is proposed that aims to trade-off between node delay, link reliability, and the consumed energy. It is proved that ensuring the reliability of paths will decrease the congestion and thus latency to reach the sink. In [7], a new composite PRL metric is proposed that takes into account delay, hop count, link quality, and expected transmission count (ETX). Furthermore, [8] proposed a new RPL metric that is aware of congestion and can select the paths according to nodes' dynamic traffic. This approach contributes to congestion mitigation as well as latency reduction.

In this thesis, we propose and evaluate the performance of a new delay- and energy-aware RPL protocol on a real AMI network (which is currently implemented using the PLC PRIME standard). The network topology is simulated as a wireless network to give a vision for a possible future combination of wired and wireless links. We use the COOJA simulator to simulate our wireless network, which is used with Multi-path Ray Tracer Medium (MRM) radio environment. We experiment with different objective functions in order to limit the latency under a prespecified threshold. Our modified objective function also results in reduced energy consumption, as we will see later in the coming thesis chapters. Our preliminary results give insight into future enhancements, adoption, and combining RF and PLC links into a single hybrid routing metric. Moreover, we consider the placement of repeater nodes in the network to meet the latency constraint. The

repeater nodes will be used to offload the traffic at the congested network nodes, which is the main cause of violating the latency constraints. Finally, we proposed a new asynchronous transmission algorithm for nodes' data packets that contributes to the latency reduction on top of the routing solution.

1.1.1 Related work

Low Power and Lossy Networks (LLNs) is a group of interconnected embedded devices with limited power, processing, and storage. Such limited network resources make the selection of an appropriate routing protocol a challenging task. As the hybrid network architecture exhibits the characteristics of LLNs, some constraints and unique routing challenges should be taken into account. The varied applications mean different characteristics and conflicting requirements such as latency, reliability, and traffic overhead. Furthermore, the dominant communication pattern in LLNs is multi-point to point (MP2P) as well as alternating to other patterns like P2P and P2MP. Also, the operation of LLNs exhibits deployments with different densities, i.e., scalability issues, and hence the routing should handle relevant, diverse cases. The power constraints in LLNs force the routing to ensure low energy consumption that sends useful updates to refresh routes. A routing protocol that can achieve the LLNs requirements is the RPL. There are several routing protocols used for wireless mesh networks. The routing in power line communication (PLC) may inherit some of those protocols to optimize path selection according to its unique specification. For instance, layer 3 of the PRIME PLC standard requires proactive routing. Another study in [9] presents a comparative analysis of different routing protocols in WSNs. Ad hoc On-Demand Distance Vector Routing Protocol (AODV) exhibits the highest delay and average energy consumption among all. Optimized Link State Routing Protocol (OLSR) is characterized by its low power consumption, packet loss, and average delay. The network characteristics basically control the choice of routing algorithm. For power saving, the Power-Aware Multi-Access (PAMAS) protocol is a

good choice. However, for fault-tolerance purposes, the Temporally Ordered Routing Algorithm (TORA) can be the optimum path selection algorithm. Few papers compared RPL to other related protocols. The results of [10], [11], showed that RPL outperforms its counterpart; The Lightweight On-demand Ad hoc Distance-vector Routing Protocol – Next Generation (LOADng) in terms of overhead, delays, memory, and route formation. The study in [12] also proved that RPL exhibits lower delay and higher packet delivery ratio (PDR) than AODV.

Since our smart metering network is considered a type of LLN, we used RPL protocol to improve its performance. Furthermore, RPL does not impose the use of a specific default objective function and opens the door to select it according to the defined application and system constraints [13]. The recent physical alliance release, called Wi-SUN with its Field Area Network (FAN) profile, contains the RPL in its network layer and is strongly recommended as a solution for the hybrid network performance enhancement. The authors in [14] suggested using multiple RPL instances inspired by existing RPL mechanisms to choose the best interface for routing per node. The same paper suggests Parent Oriented Design (PO) that aims to merge the two technologies into a single hybrid metric. Another study in [15] introduced the concept of MAC layer extension for both RF and PLC technologies. It basically targets applying some modifications to the RF frame structure without changing MAC components. Carrier Sense Multiple Access (CSMA) is applied conventionally in the contention-free period (CFP), which represents the interval of all guaranteed time slots of all network nodes. At the same time, RF CSMA is to be applied in the SCP to replace scheduled channel polling.

1.2 Organization of the thesis

This thesis presents some work and contributions in network optimization and performance enhancement in terms of end-to-end delay and energy consumption. A new proposed composite RPL metric is used to improve the system communication in the network layer. Also, a novel asynchronous transmission scheme is proposed for PLC and wireless AMI networks to reduce the meters' latency.

The thesis is organized as follows:

- Chapter (2) presents a literature review of the Power Line Communication (PLC) systems and discusses different wireless metering technologies used to enhance the performance of Low Power and Lossy Networks (LLNs). Also, it presents the proposed hybrid RF and PLC network model and provides the suggested solutions to optimize the hybrid model performance by exploiting the advantages of both RF and PLC technologies.
- Chapter (3) discusses the main requirements and constraints of smart metering applications. Moreover, a new enhancement to standard RPL termed Delay-Aware (DA-RPL) is presented and evaluated on a realistic wireless network to ensure low nodes' latency as well as link reliability. We also propose repeaters' placement algorithm to provide sufficient congestion mitigation and meet a predefined delay threshold on a node basis. We show that the performance of DA-RPL is promising in terms of end-to-end delay and energy consumption.
- Chapter (4) proposes a novel asynchronous transmission scheme for PLC and wireless AMI networks. By controlling the transmission times of data packets, we show that we can achieve significant reductions in the end-to-end delay and meet latency requirements. The idea of the transmission is based on avoiding anticipated congested routes by referring to the synchronous constructed Destination Oriented Directed Acyclic Graph (DODAG).

- Chapter (5) provides the conclusions of this thesis and proposes some directions for future research.

1.3 List of contributions of this thesis

- We introduce a new RPL additive routing metric called Delay Aware DA-RPL in order to achieve the target latency constraints and save consumed energy.
- We propose to insert some repeater nodes in the simulation environment to enhance the latency performance.
- We compare the performance of DA-RPL with three different objective functions. Interestingly, we show that DA-RPL demonstrated the best latency and energy performance and succeeded in meeting the predefined system requirements.
- We propose to use the asynchronous transmission scheme of the data UDP packets to mitigate the expected congestion, decrease packet loss rate, and improve the end-to-end delay for each node or smart meter in the network. We prove that this transmission scheme is sufficient for significant delay reduction and traffic overhead alleviation.

Chapter 2

Smart Meter Communication

This chapter is divided into three sections. In the first section, we discuss the general PRIME Power Line Communication PLC specifications in detail and present the PLC restrictions. It also discusses common wireless metering technologies used to enhance the performance of Low Power and Lossy Networks (LLNs). A proposed hybrid RF and PLC network is provided along with its suggested methods to optimize the hybrid system performance by exploiting the advantages of both RF and PLC technologies.

2.1 Review of PRIME PLC specifications

2.1.1 Physical layer

Powerline Intelligent Metering Evolution (PRIME) is mainly the most common type of narrowband power line communication and is considered one of the best mature technologies in automated smart meter reading. Its physical layer is based on Orthogonal Frequency Division Multiplexing (OFDM) with a carrier scheme that depends on differential phase-shift keying. The PRIME sampling frequency is located at 250 KHz with carrier frequencies ranging from 42 to 89 KHz. PRIME provides high data rates that range from 40 Kbps up to 1 Mbps. The PRIME service nodes tend to form a tree topology rooted at the sink, called the base node. It supports bi-directional communication and has high immunity to noise and interference thanks to its unique modulation technique [16].

Factors affecting physical performance

Many factors affect the PRIME performance in which the impedance and line noise are the most harmful ones. A careful design should consider the impact of the impulse noise and interference as well as the network size to ensure a reliable network. The PRIME specifies an inter-leaver to mitigate burst noise and enhance system performance [17].

2.1.2 MAC layer

PRIME network topology construction begins with the root base node (BN), which broadcasts periodic beacons to all service nodes. Once received, nodes registration and route selection processes occur simultaneously. However, PRIME does not define any maintenance criteria to the formed tree topology to keep it up-to-date. Instead, it tends to send periodic control 'keep alive' messages to monitor the registered nodes. This technology basically uses Automatic Repeat Request (ARQ) as a recovery mechanism to manage and control the number of re-transmissions for unacknowledged packets and uses a predefined timeout to cancel the registration of nodes from topology rooted to the base node. In addition, PRIME supports multi-hop proactive routing.

2.2 Limitations of PLC

power lines do not necessarily offer a secure media, and it is sensible to disturbance. Its low transmission speed characterizes PLC, and this is a critical point in smart metering applications. With the presence of numerous elements on a power line network, data attenuation is likely to be an issue. High costs of residential appliances: the cost of a power line network modem is not always competitive with the cost of a standard modem used to connect to a phone line network. The greater amount of electrical noise on the line limits practical transmission speed.

2.2.1 The challenges of PLC with AMI

The Advanced Metering Infrastructure (AMI) is an important part of the Smart Grid Communication (SMG), where the Smart Meters (SM) are connected and rooted to a Data Concentrator Unit (DCU) that collects user energy billing information through dynamic bi-directional communication. In general, the DCU functions as a gateway between the Wide Area Network (WAN) and the smart meters. Since PLC is sensible to noise and interference, it does not achieve the required specification of a high-percentage coverage area and reading speed. Furthermore, the PLC-based mainly on OFDM and use narrowband (NB) frequency is more vulnerable to signal reduction due to impulsive noise, background noise, and Narrow-Band Interference (NBI). On the other hand, PLC technology has a full hold on the utilities, whereas its RF counterpart only uses public frequency bands for its operation.

2.3 Wireless metering technologies and standards

2.3.1 Wireless Meter Bus

Wireless Meter Bus (WM-BUS) is a European standard used to manage the communication between different smart metering applications. It is generally characterized by its robust, long-range as well as efficient power design. It operates in the license-free ISM bands 169 MHz, 433 MHz, and 868 MHz. The latter band reflects the main advantage of wireless meter bus. It provides a good radio frequency range with suitable antenna size and mitigates such interference with higher communication distances [18].

WM-Bus has its unique star network topology and provides six transfer modes representing particular applications [19]. The basic WM-Bus stack includes physical, data link, and application layers, which can be extended for advanced security purposes. The 868 MHz band offers high penetration

through concrete walls, which alleviates the suppression of transmitted signals. The WM-Bus solution provides reliable hardware and firmware for smart grid applications. High-performance implementation's core components are low power microcontroller (MCU), high-performance transceiver, a modular software stack, and suitable deployment tools to evaluate and deploy the solution. Wireless meter bus technology is originated from the metering bus (M-Bus). Although it offers implementation from the physical layer to the application layer and left the network layer without a defined specification, it provides an important environment to use it in the industry. Therefore, many companies tend to design their own network specification that suits their predefined requirements by manipulating the embedded stack. Usually, smart electric meters are placed near households, and there is always a need for mutual collaboration between distributors to meet coverage and power quality needed. It is beneficial for system performance to adapt a wireless meter bus that can also operate as a concentrator to collect data efficiently. Considering all deployment and implementation scenarios, no wireless technology, even wireless meter bus, will win in all scenarios and provide good performance in all aspects.

However, using a wireless meter bus enables the transmitted signal to seep through concrete walls with consuming lower energy. This feature is thanks to the ability of WM-Bus to operate in the 868 MHz band. Furthermore, this band offers a good coverage area of transmission, avoids GSM interference, enables reasonable antenna diameter, and provides a sufficient radio frequency range.

2.3.2 ZIGBEE

It is a standard that is commonly used in wireless sensor networks and is based on IEEE 802.15.4 specification. It is mainly specified by its low power, low data rate, low cost, and easy deployment. ZIGBEE operates in three ISM bands; 868 MHz, 915 MHz, and 2.4 GHz, with data rates of 20 Kbps, 40 kbps, and 250 Kbps, respectively [20]. It basically supports three

network topologies; star, mesh, and tree and provides secure and interoperable communication between end devices. ZIGBEE stack comprises physical and MAC layers defined by IEEE 802.15.4 and network and application layers specified by the ZIGBEE alliance [21]. It uses Direct Sequence Spread Spectrum (DSSS) transmission technique and allows multiple channel access with CSMA/CA. Thanks to its capability of supporting a large number of nodes, ZIGBEE is used in many real-time monitoring and control systems.

ZigBee is known to have several significant advantages, including but not limited to the delivery of customers' use of energy, gas, and water in an automated, monitored, and controlled manner. It can also be used to monitor patient status and many customer devices like computers and their features. It enables interoperability between different wireless technologies. Furthermore, it offers up-to-date pricing improvements, as well as prepaid services. However, ZigBee is not the best candidate to support communication through concrete walls as it is commonly used in the 2.4 GHz band. Moreover, it still provides poor network synchronization that consumes and wastes nodes' power.

2.3.3 LoRa

LoRa is a long-range wireless protocol dedicated for low power wide area network. LoRa stack defines mainly MAC and physical layers. The latter is responsible for the modulation technique that is based on chirp spread spectrum (CSS) with integrated forward error correction to provide more interference immunity and higher sensitivity to the receiver [22]. LoRaWAN defines the MAC layer and provides data rates that range from 250 bps up to 50 Kbps determined according to the aimed communication range. The predefined selection of the triple; code rate (CR), spreading factor (SF), and bandwidth trades off between data rate and communication range [23]. The prime advantage of LoRa is characterized by its capability to cover up to 15 km and demodulate signals below the noise floor.

LoRa supports bi-directional communication between base stations and end-users' nodes. It operates in the unlicensed ISM band with a spectrum of 920-923 MHz. The chirp frequency band is used to recover the information signal with a variable bandwidth that can be programmed in the initial settings. A suitable combination of the spreading factor and code rate affects the coverage area and the end-to-end delay of data packet transfer but at the expense of the interference immunity. LoRa technology employs the smart ALOHA technique to save nodes' energy consumption. It allows the transmission of packets only when information is needed to be transferred; otherwise, it prevents it. This asynchronous method extremely enhances the smart meter lifetime and made LoRa one of the best wireless technologies for battery-constrained nodes.

Thanks to the star topology and adaptive data rate mechanism that LoRa uses, it has the ability to optimize the battery lifetime and data rate efficiently. This, in turn, boosts the LoRa capacity and ability to collect plenty of information from a dense network. LoRa employs AES encryption and offers the application and network security to ensure data protection and authentication. However, this technology does not usually meet low delay requirements and does not support high data rates. Furthermore, its sending capability is restricted by its duty cycle.

2.3.4 Wi-SUN

Wi-SUN is a wireless communication technology designed for smart cities and IoT applications. It operates basically in frequencies that range from 470 to 928 MHz and covers up to five kilometers. IEEE802.15.4g defines Wi-SUN's physical specification characterized mainly by frequency shift keying (FSK) modulation and data rates from 50 Kbps to 400 Kbps relative to the frequency of operation. The key standard IEEE802.15.4e specifies the low energy (LE) consumption MAC, which uses CSMA/CA for asynchronous transmission. The upper layers of Wi-SUN stack are defined by IETF profiles under five working groups (WGs), in which the FAN WG

includes the common RPL protocol in its network layer [24]. For configuration, frame messages are sent between devices, using a predefined trickle timer to discover neighbors. The timer is identified to manage the frequency of transfer and mitigate the anticipated collision. One of the major disadvantages of Wi-SUN FAN is the long time taken for the configuration process, making it a poor candidate for managing communication between several nodes or smart meters in advanced metering infrastructure.

On the other hand, Wi-SUN technology saves energy and supports suitable data rates and multi-hop communication in both uplink and downlink directions. In addition to its ability to provide efficient propagation features, it can cover large distances. Therefore, the wireless smart utility network is a promising technology for hybrid PLC and wireless AMIs as it achieves low power, low link latency, and high deployment scalability.

2.3.5 Wi-MAX

Worldwide Interoperability for Microwave Access (Wi-MAX) is a wireless technology that is based on IEEE 802.16. It supports high data rates and a large area of coverage. The variability of its service options combined with its QoS features enables it to achieve different smart grid implementation requirements. A study in [25] and [26] proposed a hybrid wireless WLAN-Wi-MAX frame for smart metering traffic collection. This structure enables more extension for network coverage and link quality enhancement. For smart metering applications, the data is transferred from a specific smart meter towards the concentrator and collector point using the constructed mesh topology. The Wi-MAX station is used to carry the information to the base station.

In fact, Wi-MAX outperforms other wireless technologies in some aspects due to its unique features. First, Wi-MAX can cover a distance up to 48 Km, with one BS. For this coverage area, it offers a speed that reaches 70 Mbps. Moreover, the data rate is not highly affected by the channel split

among multiple customers. Thanks to the built-in quality of service (QoS) for WI-MAX, it provides the best QoS among other technologies.

2.3.6 LTE

Long Term Evolution (LTE) is a standard wireless technology in the field of the Internet of Things (IoT). It can be integrated with other technologies to join the smart metering communication efficiently. LTE offers low delay, high network capacity, and fast data rate. It also has the ability to enhance the nodes' lifetime through adopting OFDMA scheme in the downlink and single-carrier FDMA in the uplink. LTE supports a variety of modulation schemes as well as multiple-input multiple-output (MIMO) communication. It supports a wide bandwidth range of 1.4 to 20 MHz and enables enough spacing between sub-carriers up to 15 KHz.

The prime challenges of LTE in smart grid and smart metering communication can be summarised as follows: first, the physical downlink control channel (PDCCH) is used mainly to manage the scheduling information of each sub-frame. The number of control information messages will, in turn, increase in proportion with the number of users. This will finally cause the exploitation of resources other than the data resources and may not be enough for a great population of consumers to schedule all of them. Second, when users are randomly requesting channel access, especially in dedicated up-link absence, a new problem is initiated. If asynchronous requesting is allowed to multiple users, a collision may happen between their preambles, contributing to higher access latency and lower PDR. In smart metering, sounding reference signal (SRS) also greatly impacts the whole system overhead, especially for a high population of end-users. This issue can be mitigated by enlarging the SRS period or interval as possible even if there is no active communication. LTE is vulnerable to possible coverage decline, especially in smart metering, which is due to the node deployment with very high density. This will, in turn, have a negative influence on the whole system in terms of interference and coverage. Furthermore, the recent version of LTE is much more expensive than other wireless metering

technologies.

2.3.7 6LoWPAN

IPv6 over Low-Power Wireless Personal Area Network (6LoWPAN) represents a simple, low-power, and cheap system implementation that offers packet transmission between devices functioning under IEEE 802.15.4 standard. It uses a maximum length of IPv6 PPDU of 128 bytes to conform with IEEE802.15.4 MAC frame length. IPv6 utilizes a header size of 40 bytes. In the protocol stack of nodes, the adaptation layer serves as the gateway between 802.15.4 MAC and the IP layer. It is responsible for fragmenting packets, compressing the header, and then reassembling them. The ZIGBEE standard's main goal is the reduction of consumed power to use a simple-design transceiver. The data rates supported are low, especially in the frequency bands 868 MHz and 915 MHz. Also, it supports a data rate of 250 Kbps in the 2.4 GHz band. On top of that, 6LoWPAN keeps up CSMA/CA for channel access when synchronized nodes use beacons.

2.4 Hybrid RF and PLC network

Recently, most smart metering networks use more than one communication technology to achieve better system performance. Each of which has its own specifications characterized by its unique OSI model. While the PLC technology is characterized by its low deployment cost, it is sensible to interference and impulse noise that degrades the system reliability. The wireless radio frequency network may also suffer from noise and interference; it offers higher data rate transmissions but with lower reach-ability. Therefore, utilizing the hybrid of both wireless RF and PLC is useful in terms of achieving more system reliability. This returns to the fact that there are no symmetric characteristics of the RF and PLC links.

The hybrid RF and PLC network is recommended as a general solution to achieve more system reliability and higher coverage distances. However, this suggested architecture needs further studies and adaptations in order

to optimize the system performance. The authors in [27] treated the hybrid network architecture as each technology is separated from the other and has its own communication section, but this is usually not the real implementation case. Furthermore, the key to accomplishing more system reliability is to interconnect the two technologies so each can overcome the drawbacks of the other.

The current implementation of the hybrid RF and PLC network tends to use different wireless meter technologies to achieve the system specification in their vicinity of deployment. They may also be used as repeaters to amplify the transmitted signal between a certain node and the destined roots. Consequently, the resultant network may be a mixture of PLC links that are characterized by their tree topology architecture and different wireless technologies such as wireless meter bus, Lora, and Wi-SUN specified by their mesh connection.

The hybrid of wireless RF and PLC network is mainly affected by the application characteristics and the environment they are immersed in. This, in turn, raised the challenge of combining the hybrid network into a single infrastructure that is more reliable. Power line communication is mainly more susceptible to interference and noise and suffers from low data rates, whereas its short-range characterizes RF network. Hence, using single wireless communication will encounter reach-ability challenges, and a single PLC network will be constrained with its specification. Consequently, recent studies and papers began to suggest different solutions to apply and implement the hybrid network in real communication to benefit from each network's advantages in such a way each can compensate for the drawbacks of the other.

The RF and PLC networks can both be categorized as Low Power and Lossy Networks (LLNs). LLN is a group of interconnected embedded devices with limited power, processing, and storage. Such limited network resources made the selection of an appropriate routing protocol a challenging task. As the hybrid network architecture exhibits the characteristics

of LLNs, some constraints and unique routing challenges should be taken into account. The varied applications mean different characteristics and conflicting requirements such as latency, reliability, and traffic overhead. Furthermore, the dominant communication pattern in LLNs is multi-point to point (MP2P) as well as alternating to other patterns like P2P and P2MP. Also, the operation of LLNs exhibits deployments with different densities, i.e., scalability issue, and hence the routing can handle relevant, diverse cases. The power constraints in LLNs force the routing to ensure low energy consumption that sends useful updates for the refresh of routes. The routing protocol that can achieve the LLNs requirements is the RPL; Routing Protocol for LLNs.

2.4.1 Previously Proposed solutions

There are several routing protocols used for wireless mesh networks. The routing in power line communication may inherit some of those protocols to optimize path selection according to its unique specification. For instance, layer 2 of the PRIME PLC MAC is specified by its proactive MAC routing. [28] revealed comparative analysis of different routing protocols in wireless mesh networks (WMNs). AODV exhibits the highest delay and average energy consumption among all. OLSR is characterized by its low power consumption, packet loss, and average delay. The network characteristics basically control the choice of routing algorithm. For power saving, PAMAS is a good choice. However, for fault-tolerance purposes, TORA or ATR can be the optimum path selection algorithms [29]. Few papers compared RPL to other related protocols [30]. The results of [31-32] showed that RPL outperforms its counterpart LOADng protocol in terms of overhead, delays, memory, and route formation. [33] also proved that RPL exhibits lower delay and higher packet delivery ratio (PDR) than AODV.

My proposed solution claims that the system performance optimization can take place in the network layer to use a routing protocol that works with both networks like The Routing Protocol for Low Power and Lossy

Networks (RPL). Recent physical alliance release called wireless smart utility network (Wi-SUN) with its FAN profile contains the RPL in its network layer and is recommended strongly as a solution for the hybrid network performance enhancement. [34] suggested using multiple RPL instances inspired by existing RPL mechanisms to choose the best interface for routing per node. The same paper suggests Parent Oriented Design (PO) that aims to merge the two technologies into a single hybrid metric. Generally, routing aimed to optimize the path selection in layer 3 without taking into consideration lower OSI layers. Furthermore, the insertion of extra repeaters in the network environment should contribute to the latency performance enhancement.

Nevertheless, the architecture of a hybrid network inspires the role of MAC layer in optimizing the routing performance. Consequently, suggested alternatives introduce the concept of MAC layer extension for both RF and PRIME technologies. It basically targets applying some modifications to the RF frame structure without changing MAC components. Carrier Sense Multiple Access (CSMA) is applied conventionally in the contention-free period (CFP), which represents the interval of all guaranteed time slots of all network nodes. At the same time, RF CSMA is to be applied in the SCP to replace scheduled channel polling [35]. The major advantage of this solution is the increase in network reliability and link throughput.

Chapter 3

Realistic wireless smart-meter network optimization

3.1 Introduction

The smart metering networks like RF-based systems requires a set of features that meets the predefined requirements such as latency, energy, and lifetime. Each energy meter should be able to update its consumption of gas, water, or electricity in an efficient manner. Hence, a set of requirements are needed to meet such limitations.

3.2 Routing requirements for the AMI

The smart metering applications along with its unique specifications and constraints will need a flexible and dynamic routing protocol. In [36], it is shown that the scalability is one of the most important requirements for the routing protocol especially when used for LLN. The suitable routing should not allow the linear and direct proportionality between the routing scale and the network density. Furthermore, good routing protocol should be reliable for LLN features. For instance, the link quality should be taken into account in order to adapt itself with dynamic and fast change of this metric with time.

For smart grid communication, specially under the umbrella of smart metering applications, the consumed energy of nodes should be highly

considered in the routing selection and topology construction. Therefore, knowing that most of smart meters are battery-constrained, it is necessary to enhance and network lifetime and also adapt the routing to adapt to dynamic variations efficiently. In other words, it should reduce the traffic overhead of control messages and ensure up-to-date maintenance. On top of that, the routing for LLNs should avoid loops as possible as to save more nodes' power and accelerate more robust topology construction. This can be achieved through the use of ranks or sequence numbering.

3.3 Routing protocol for low power and lossy networks (RPL)

In this chapter, we present an overview of the routing protocol for low power and lossy networks (RPL) and its key role in improving the system performance of the hybrid wireless and wired network.

3.3.1 Overview of RPL

RPL is a proactive distance vector based routing protocol designed for low power and lossy networks (LLNs) that are composed of resource constrained nodes. RPL protocol can operate in both RF and PLC networks and considered as a solution for networks with limited power, low data rate, and high packet error rate (PER) [37]. It allows the construction of the topology graph named as Destination Oriented Directed Acyclic Graph; which is a tree rooted at sink without cycles. The tree topology is built based on predefined objective functions (OFs) that allow the nodes to select the best parent for forwarding packets based on some routing metrics such as latency, hops, or energy. The main RPL messages as well as the Objective Function play a key role in forming the DODAG and enabling routing.

This protocol is mainly done through four phases. The first begins with broadcasting the routing configuration parameters included in the DODAG Information Object (DIO) message by the root. All the nodes that receive the DIO message are able to construct their own routing table for future upward or downward communication. The second phase aims to build the DODAG topology using node rank computation. The rank represents the location or radius of each node relative to the root and aims to prevent loops in the constructed tree topology [38]. Similarly, each node sends Destination Advertisement Object (DAO) to form the shortest path to the DODAG root. The objective function defines some algorithms to constrain the routing metrics contained in the received DIO metric container. Each node selects the minimum rank neighbor as its preferred parent for forwarding packets. DODAG Information Solicitation (DIS) message is used by nodes

that want to join the DODAG. RPL protocol uses trickle algorithm to determine how frequently the DIO messages are sent to enable more DODAG stability that ensures that constructed topology is up to date and verify energy efficiency [18].

3.3.2 CONTIKI RPL

RPL routing protocol is commonly used in the IoT community as it does not impose the use of a specific default objective function and opened the door to select it according to the defined application and system constraints. One of the implementations of the RPL is the CONTIKI operating system where the RPL uses minimum rank with hysteresis objective function (MRHOF) as the default objective function (OF) with the expected transmission count (ETX) metric for rank computation. Even for static network nodes, there may be some dynamic changes in the metric which may cause instability in the constructed DODAG. Hence, MRHOF ensures that the selected preferred parent has the minimum cost while using hysteresis to prevent excessive churn in the network [39]. ETX is an estimation for the average number of transmissions to ensure correct delivery to the destination. It is calculated by actively sending probes between nodes within specified time window.

The Contiki RPL uses a couple of operating modes. The first storing mode is appropriate for nodes with constrained storage capacity, as it allows bi-directional communication between source and sink nodes only. Hence, the whole routing and topology data is known only by the sink node. That's why the central sink node is used mainly for routing all nodes. However, the storing mode tend to allow broadcasting routing and child nodes' parameters to contribute to the final DODAG construction. Contiki implementation of RPL allows memory optimization through the employment of dynamic allocation. Also, it enhances the network energy and lifetime by switching nodes to sleeping mode in the case of idle events. A periodic check for the channel is allowed for this manner. Furthermore,

CONTIKI-MAC allows bi-directional communication between network nodes at low power and with real-time simulation, thanks to the contiki rtimer. Contiki supports IPv4, IPv6, unicast, broadcast over single and multiple hops using microIP and rime stacks.

3.3.3 RPL with RF

Due to the recent growth of the Internet of Things (IoT), combined with the availability of different wireless platforms, RPL has been intensively studied and evaluated. Smart metering systems may generally require low latency, and high reliability for most of its applications. Evaluation of RPL can be divided into two sections: general study and comparison with other routing protocols, and RPL enhancement approaches to improve its performance. In order to evaluate the RPL performance accurately, there should be a precise emulation and simulation of realistic environment. This necessitates a precise link failure model for attenuation and interference as well as acquiring a realistic link layer information on real deployment.

Several papers have used the COOJA simulator along with its supporting CONTIKI OS to evaluate RPL. A study in [21] have conducted an evaluation on randomly generated 86 nodes rooted to single sink node. The study observed the performance of link quality, end-to-end delay, and traffic overhead. It also reveal the efficiency of RPL with its local repair mechanism and using a single ETX metric for constructing the topology. Furthermore, the authors in [40] proposed some enhancements on RPL specially on MRHOF and clustering technique. The results show performance enhancement of delay, RDR in conjunction with the standard RPL. Also, with clustering, the consumed energy is reduced. Another study in [41] relates the network traffic performance in terms of latency with the used RPL objective function. For example, when MRHOF along with the ETX metric, the network ability to expand is reduced when compared with OF0 specially if the number of nodes is greater than 100.

In [42], the observations showed that there is an inverse proportionality

between the density of the network and the PDR or stability. The study also showed that the existence of links with low robustness leads to a high rate of preferred parent change under RPL, which affects the stability of DODAG. Another study in [43] focused on the congestion and load balancing issue at some forwarding nodes. The neighbours of the sink node are more likely to send their data packets than other nodes in the network. The congestion mitigation necessitates using a queue utilization factor that includes multi-casting the congestion data in RPL DIO message. Although this approach increased the complexity of parent choice, it offers enhancements of network scalability and packet delivery. A study in [44] concerned with RPL periodic DAO messages and proposed a new approach in order to dynamically optimize the value of Delay_DAO in accordance to the network density and scale. The optimization can be adapted such that the rate of constructing DODAG is not slow and also RPL still enable suitable reaction to DODAG changes. As a result, DAO congestion is mitigated specially in large networks. Two different studies in [45] and [46] focus on the effect of used routing metric, under MRHOF, on the stability of the network. Results show that the network stability is reduced under ETX metric. However, hop-count metric enables more stable network at the expense of selecting inefficient links.

Two authors in [47] and [48] proposed new enhancements and modification on RPL. The first focuses on the use of both artificial intelligence and cognitive radio in order to optimize the selection of paths from a certain node to the sink. They used latency and hop metrics in their evaluation of the AMI scenario. The authors also reveal that cognitive radio contributes to the improvement of end-to-end delay, consumed energy and PDR but with extensive alteration of the standard RPL. In [49], the performance of a new proposed RPL metric is evaluated with ETX metric. The new metric comprises four path properties which are link quality, link asymmetry, retransmission and RDR. The simulation implies the implementation of smart grid system and the evaluation is conducted for the new metric in both the

existence and absence of ETX. Results reveal better network performance when the ETX is excluded in terms of the stability. Similarly, the study in [50] introduce a new RPL OF that aims to combine the effect of several routing metrics using fuzzy logic. When compared with its MRHOF counterpart, it shows better network lifetime, latency and PDR but at the cost of more network instability.

In the standard RPL, a trickle timer is adjusted to preserve the DODAG causing a network overhead. In a way to reduce such overhead, [51] introduce a new Trickle-L2 approach aims to reduce to the network traffic through the control of the waiting time of nodes for a certain path quality or the transmission of control messages. For smart grid communication, nodes may be powered through batteries specially for smart metering applications like gas and water meters. Therefore, [52] proposed a new RPL metric that is based on two routing costs; ETX and remaining energy of nodes. The study demonstrate that network lifetime in improved by 12%. Another study in this aspect introduce a new RPL extension that takes both energy and battery index into account. This RPL modification show improvement in network consumed energy.

3.3.4 RPL with PLC

In [53], a new modification on RPL is proposed by introducing a new objective function that aims to suit the rank calculation to the constrains and limitations of power line communication. The simulation environment is configured using real field measurement. The results show better constructed DODAG at the expense of higher traffic overhead.

The first application of RPL in a PLC medium using communication that is based on IEEE 802.15.4 ZIGBEE and IPv6 under 6LowPAN was proposed in [54]. This includes implementation of a real test-bed scenario under CONTIKI operating system. This simulation showed better enhancement for the end-to-end delay by about 45% under ETX metric when compared with the uncompressed IPv6. In [55], 6 PLC nodes rooted to a single sink node are

simulated under COOJA simulator. The simulation results are then compared to a proposed realistic RPL scenario. The outcome confirmed that the simulation demonstrate lower latency performance than the real scenario due to the increase of induced path layer retries.

Another study in [56] proposed a comparison between RPL and LOAD routing protocols in G3 power line communication standard. The evaluation is conducted by both realistic test-bed scenario and OPNET simulation. Results indicate similar performance for both scenarios with higher simulation time for RPL due to its reactive routing.

Furthermore, [57] proposed a channel occupancy metric that takes into consideration different modulation schemes. The study is conducted with the power line communication IEEE 1901.2 standard. This new metric reveal higher network stability and enhanced forwarding performance when compared with ETX metric under MRHOF.

On top of that, proposed techniques of polling schemes are introduced in [58]. This proposal provides an optimization solution in the application layer. The automatic reading is tested and evaluated through a simulated PLC environment with one Data Concentrator Unit (DCU) and under LOADng and RPL protocols. The outcome of the implementation demonstrate enhancements in the speed of reading as well as the ability to scale up the network with higher and better reading performance.

3.3.5 RPL simulation

There are different network simulators dedicated for the field of IoT applications and supporting wireless sensor networks. NS3 and COOJA are widely used wireless network simulators specially in the field of IOT.

A. Network Simulator 3 - NS3

It is a discrete-event simulator supporting different internet systems and applications. Building a network with its related routing protocols necessitates adapting existing NS3 modules as well as creating new ones. Specifically, the PRIME PLC network is built by creating new classes, examples, and tests to emulate the PRIME parameters and related network components. However, the wireless RF network can easily be built using existing models. The implementation of RPL routing protocol needs building a new module. Since RPL is not supported in the latest release of NS3, developers suggest a full RPL skeleton that is compatible with NS3 core files. Since the hybrid network simulation is highly dependent on RPL, the idea of pursuing with NS3 begins to vanish because the developers expected to completely implement it within 1 year. COOJA is the alternative network simulator that implements RPL protocol and offers friendly graphical user interface (GUI).

B. COOJA - Contiki network simulator

It is based on Contiki operating system and designed for wireless sensor networks (WSNs) and IoT applications. Cooja provides different simulation mediums each has its unique characteristics, tools, and plugins. The most common medium is the unit disk graph medium (UDGM) that uses signal strengths to limit transmission ranges. For our simulation case, in which signal attenuation and real time environment parameters are given, Multi-path Ray Tracer medium (MRM) is the best choice. MRM medium has mainly two plugins: settings, and MRM environment. The settings window enables to insert all important simulation parameters like background noise, path loss model, signal attenuation, common transmission power and so on. The second plugin provides the ability to draw the different types of attenuation between each pair of nodes. Then, the corresponding Received Signal Strength Indicator (RSSI) is demonstrated after the effect of

distance, transmission power, and attenuation. In order to enable transmission power on a node basis, a common sending power is set to all nodes initially then a node's push button is used to increase or decrease it. This way help offer an insight of the minimum and sufficient power that can be used to achieve the system requirements on a node basis. Unfortunately, the COOJA simulator does not offer the option of automated transmission power adjust per node, which should be deemed the optimum.

The proposed composite RPL metric

To achieve the predefined system requirements, especially the latency constraint which is 200 milliseconds, the latency is used first as the objective function. However, the simulation results demonstrate violations of some network nodes. This is because the delay metric may use undesired paths and hence increasing the number of re-transmissions and the packet loss rate causing the final end-to-end delay to exceed the predefined threshold. Therefore, the proposed Delay-Aware RPL metric (DA-RPL) is introduced. It is a combination of ETX, delay, and energy. This new additive metric is given by

$$DA - RPL = \alpha(ETX) + \beta(delay) + \gamma(energy), \quad (3.1)$$

where α , β , and γ are the relative weights assigned to the three metrics. Taking into account that the considered metrics are different in their ranges, the metrics values are normalized to prevent the domination of one specific metric. For example, ETX metric is normalized to $(1 - 1/ETX)$, and the consumed energy is normalized to $1 - 1/(\text{remaining energy})$. By manipulating the coefficients and then choosing the best weights, the final constructed and converged DODAG topology is expected to achieve the system requirements. Hence, the nodes can find paths with high reliability and with lower energy and delay. The considered energy metric in DA-RPL is the battery consumption which is accumulated along the simulation time. This means that the composite metric will not consider it much at the beginning, but

will take it into account more when the battery is consumed with time. Therefore, it can have a relatively small coefficient and still give reasonable energy results. As we will see later in the next section, DA-RPL will achieve the latency requirements and reduce the net consumed energy in the network.

C. Whitefield simulation environment

It is a simulation environment that integrates the simulator NS3 with CONTIKI OS COOJA simulator. It extracts the PHY and MAC stack from NS3 and work with NET layer imported from CONTIKI. I used it mainly to build both wireless and wired PRIME PLC networks separately with the function RPL routing protocol on the network layer for both. For PLC, RPL is used to build the tree topology instead of the conventional PRIME routing that is based on MAC layer. The routing functions under CONTIKI RPL and used to build the DODAG or tree topology that is directed to a root or sink without cycles. It uses different costs called Objective Functions (OFs) that optimizes the selection of routes per hop. The final target to optimize the network performance in terms of end-to-end delay and energy consumption is to build a fully functional hybrid network that is based on the comparison between both parallel wireless and wired links in terms of path cost and congestion. The exploitation of the two technologies indicates the integration or combination of both links through selecting the best cost among the average of each pair of links.

3.3.6 System model and evaluation results

I. System model

A real wireless smart metering infrastructure is simulated using the CONTIKI OS COOJA simulator. This network is located in EL-Minya in Egypt as shown in Fig. 3.1. The smart meters are emulated with Zolertia Z1 motes with a compatible cc2420 radio chip. The Multi-path Ray Tracer Medium

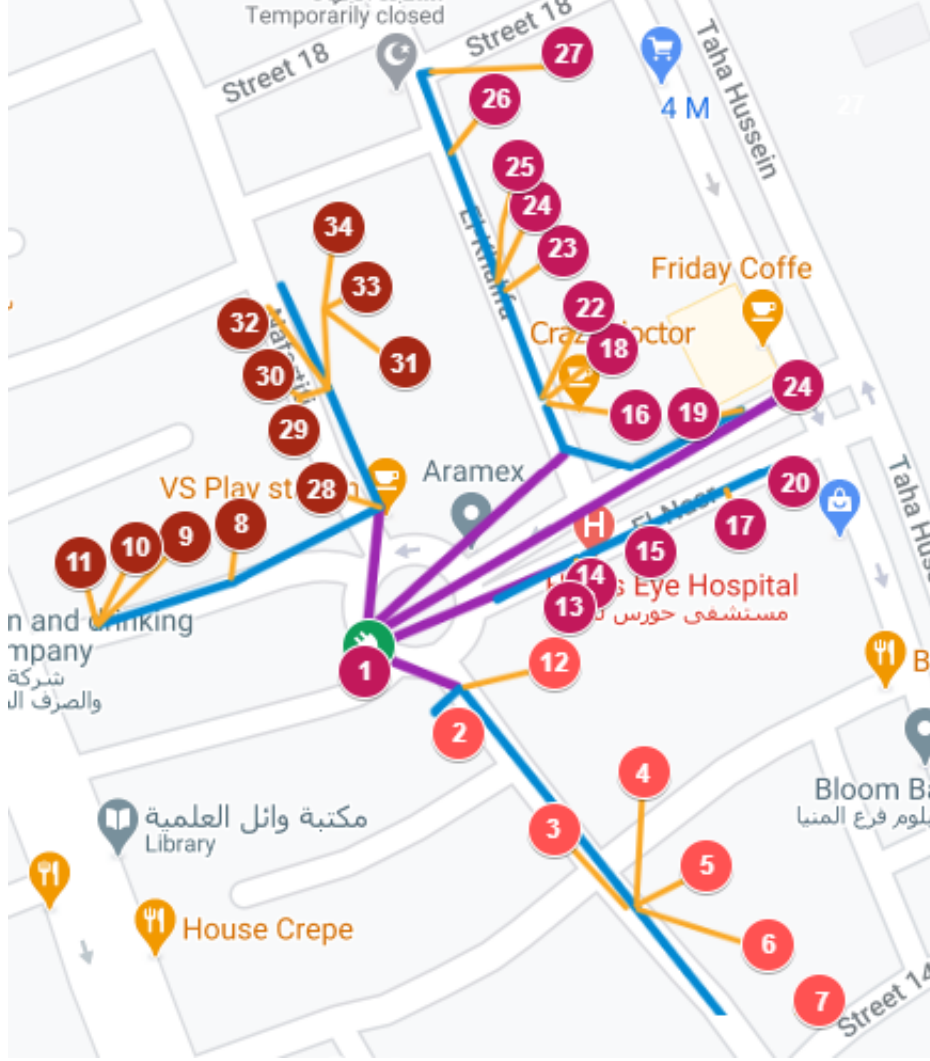


FIGURE 3.1: El-Minya PRIME network.

(MRM) is used to model the radio environment with its multi-path propagation effects and obstacles attenuation. The transmission model is scheduled every defined time interval.

Fig. 3.2 represents the built MRM model where the nodes are injected and deployed at the same locations of the actual smart meters. To have better estimates of walls' attenuation values, communication is established between two real smart meters in a building and the relative received signal strength is measured. The obstacles dimensions were estimated from a given map and inserted into the wireless network. The relative transmission-reception ratio for each node is affected mainly by distance, obstacles, transmission power, and background noise.

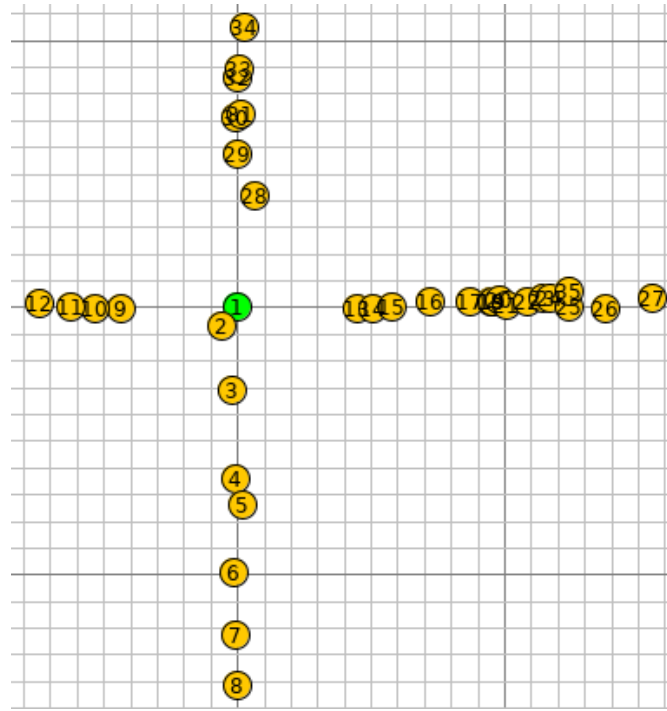


FIGURE 3.2: El-Minya network topology in COOJA simulator.

CONTIKI-MAC is used for radio duty cycling (RDC) and a channel check rate of 8 Hz is configured on all nodes to sense the radio activity without consuming high energy. The data packets of 127 bytes are sent every 30 seconds to the sink. The real traffic rate is twice a day or every 12 hours. However, this flow rate was not applied to the simulation because it will consume too much simulation time. The radio links are assumed to be asymmetric and the transmission power is configurable on each node separately. Initially, the power of packet transmission is commonly adjusted to the maximum, which is 0 dBm. The firmware of z1 motes is changed such that the transmission power can be lowered with a push-button during the simulation run. Taking into account the predefined system constraints on the end-to-end delay as well as the limitations on energy consumption, both performance parameters are calculated and evaluated. Table I presents the used simulation environment parameters.

TABLE 3.1: Simulation parameters

Parameters	Value
Simulation tool	Contiki/COOJA 2.7
PHY and MAC layer	IEEE 802.15.4
Network layer	RPL/DA-RPL
Adaption layer	6LowPAN
Number of nodes	35
Carrier frequency	868 MHz
Data rate	250 Kbps
Data rate transfer	127 byte payload every 30 seconds

II. Performance evaluation

To evaluate the performance of the proposed DA-RPL on El-Minya network, we used the COOJA simulator with the CONTIKI operating system. The main considered parameters in measurement are the end-to-end delay and energy consumption. Multi-path Ray Tracer (MRM) is the used radio model, wherein the obstacles are inserted to emulate real buildings attenuation. EL-Minya network composed of one Data Concentrator Unit (DCU) and smart meters located mostly on the ground floor. At the node level, the predefined constraint is a latency of 200 milliseconds to collect the data within an acceptable time. The results are considered when reaching the RPL convergence state where each node has a stable parent and a low CPU power. The threshold to change the preferred parent is adjusted to a suitable value to improve RPL stability.

A. End-to-End Delay

End-to-end delay is defined as the time taken to transmit a data packet from a certain node to the sink. After several simulations, and using a single RPL metric as the objective function, the latency constraint is not achieved. The

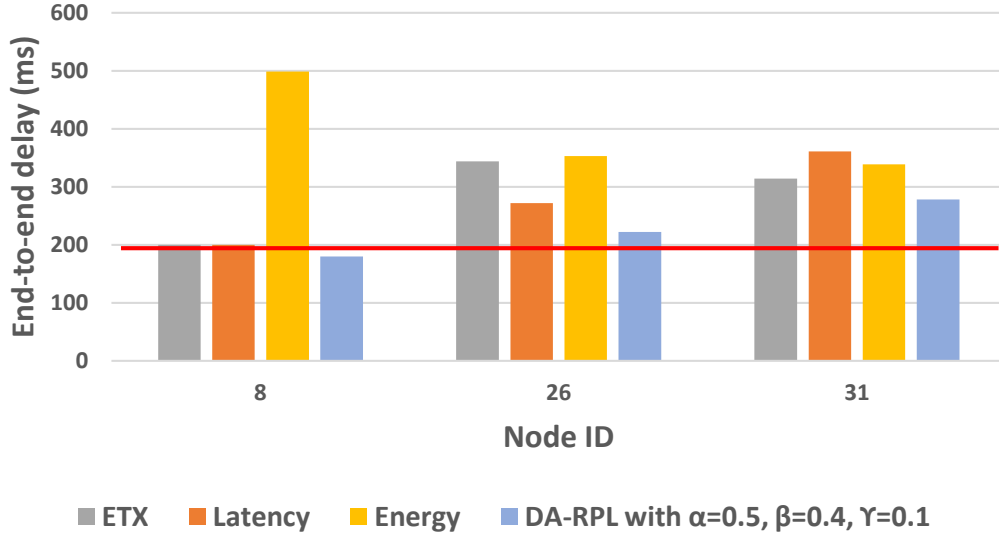


FIGURE 3.3: Nodes end-to-end delay.

second attempt is using the delay as a constraint rather than a metric and RPL tend to select paths that only meet the constraint and nullify or remove other parents. However, this way has not succeeded due to packet re-transmissions and congested nodes. Since Expected Transmission Count (ETX) defines the link reliability, it seems a good candidate to avoid congestion. Therefore ETX takes the lead of lowering the node latency as possible. Having the trade-off between energy consumption and the latency, multiple additive RPL metrics are used to save the power of the node subject to the latency limitation. The current real PRIME PLC network has a reachability percentage of almost 80 %. After simulating its RF counterpart network, the modified RPL DA-RPL with suitable metrics weights, and after the insertion of extra nodes the reachability is improved more. The extra smart meters are injected to achieve more reliable communication coverage and reach better latency results. By focusing on the nodes with high calculated latency, Fig. 3.3 shows nodes' end-to-end delay for four different routing metrics with respect to the threshold. After manipulating the metrics weights, DA-RPL shows the best delay performance and succeeded to improve the system requirement with $\alpha = 0.5$, $\beta = 0.4$, and $\gamma = 0.1$.

Repeaters placement algorithm

In the previous RPL simulation section, we have proposed a new composite routing metric to achieve the target latency constraints. However, in many scenarios and as will be seen in the simulation section, the new composite metric can result in performance gain but it may not be able to attain the desired latency constraint. We propose to place some repeater nodes in the network to enhance the latency performance. These nodes will not generate traffic over the network but can be used to route some traffic. The placement of these nodes is based on the observation that the cause of latency violation is that some nodes in the network will be congested as they will route a lot of packets. We place our repeaters to relieve these congested nodes and to provide some alternative routes to the DCU. The core advantage of this algorithm is the reduction of network congestion and nodes' E2E delay.

The extra nodes or repeaters are then inserted to the simulation environment as to enhance the latency performance further. They are injected near the concentrated nodes to mitigate the congestion and also in the vicinity of high-delay nodes in order to be their default next hop to sink. Fig. 3.4 represents the modified network topology after the insertion of the extra repeaters.

The same DA-RPL metrics coefficients are used again to check the E2E delay of nodes relative to the specified threshold. As shown in Fig. 3.5, the nodes with highest E2E delay finally achieved a latency below 200 msec. Furthermore, the average latency performance of the whole network is slightly improved after the insertion, as demonstrated in Fig. 3.6. This means that each node has a reasonable calculated latency relative to the constraint. By taking into consideration the stationary nature of El-Minya smart meters' network, the new RPL modification as well as the insertion of extra repeaters should provide a reliable, long-term solution for achieving the target latency constraints.

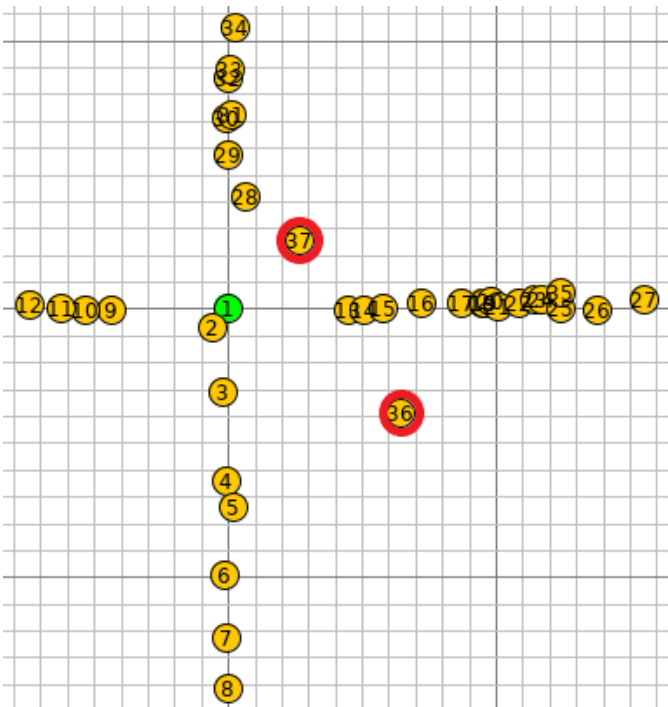


FIGURE 3.4: El-Minya network topology after the insertion of extra nodes.

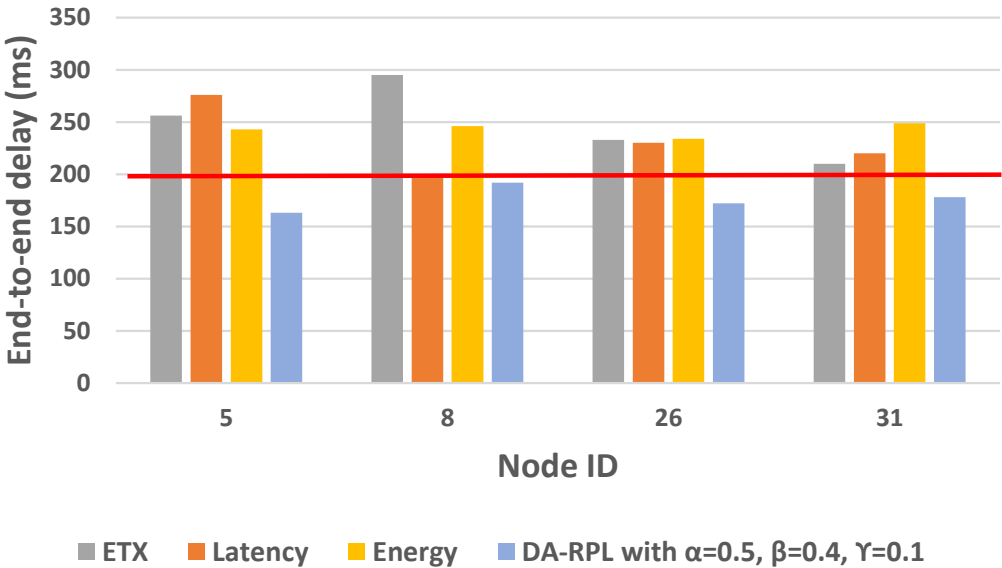


FIGURE 3.5: Nodes end-to-end delay.

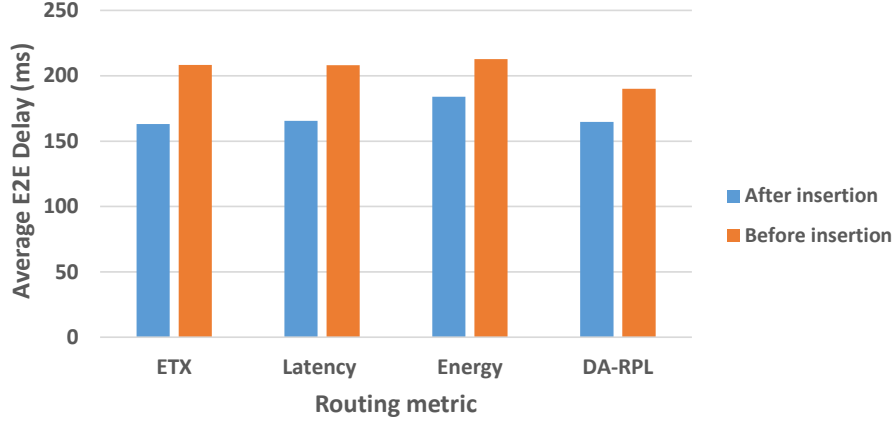


FIGURE 3.6: Network average end-to-end delay.

B. Energy Consumption

Although the energy metric is assigned the lowest weight in DA-RPL, it seems to give reasonable power consumption results because it is additive along the simulation time. For different network infrastructure, new appropriate weights can be used to optimize the system performance and meet some predefined specifications. The energy consumption of El-Minya simulated network is calculated after the insertion of extra repeaters using the CONTIKI power tracer. The calculated values are taken after the convergence of the constructed DODAG and the traffic flow of control messages begins to deteriorate. The average power consumption of some network nodes is shown in Fig. 3.7. It can be clearly confirmed that consumed power is reduced to the minimum when DA-RPL is used with suitable weights. Moreover, Fig. 3.8 shows that average power consumption of the whole network saved the best energy when compared to other routing metrics. These results show an evaluation for EL-Minya case study.

From the above, it can be seen that the modified RPL, with the selection of suitable weights, succeeded to achieve lower average consumed power than using the ETX and latency metrics (as clearly, DA-RPL has energy as part of the routing metric which is not the case for ETX and latency metrics). It also shows power consumption near that achieved by the energy metric. Since El-Minya network is characterized by its constant bit rate,

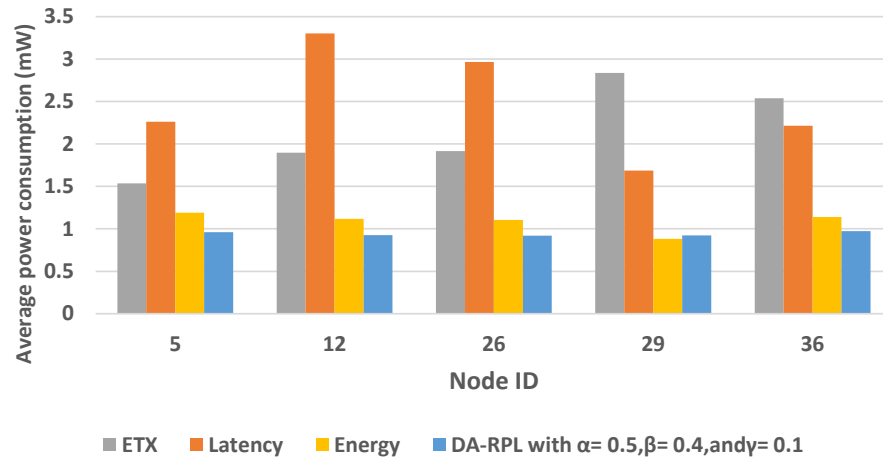


FIGURE 3.7: Nodes average power consumption.

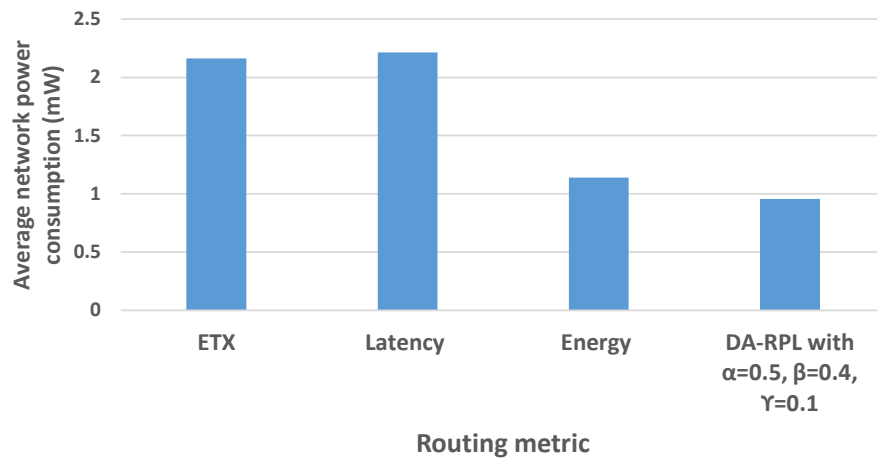


FIGURE 3.8: Network average power consumption for four different routing metrics.

static nodes, and static environment, the chosen weights can be used indefinitely unless some major changes occur. In this case, the weights should be dynamically manipulated to keep up with the changes and to ensure acceptable performance (in terms of latency and/or power consumption). Therefore, the chosen RPL weights along with the placed repeater nodes can provide an effective means for meeting the required latency constraint while achieving some energy consumption gains.

Chapter 4

Asynchronous Transmission of Data Packets

4.1 Introduction

This chapter's main idea aims to present newly proposed algorithms for data packet transmission to improve network latency performance further. The delay enhancement is based on adjusting the beginning time of data frame transmission that ensures less congestion with other meters' frames.

This chapter focuses on the methods and algorithms used to optimize the network performance in terms of end-to-end delay using ordered asynchronous transmission of packets. The proposed algorithms are based on classifying the nodes according to their given synchronous E2E delay. They are classified into high, medium, and low delay nodes as the first step of filtration. The second step aims to divide nodes into groups according to their forwarding nodes or preferred parents to the root or sink. The forwarding node or parent is determined through the RPL routing protocol and its corresponding routing tables on a node basis.

Asynchronous implementation is important for many smart grid communications, especially smart metering applications, to enhance network performance. This solution is analyzed as the realistic RF or PLC scenario offers such an option for system performance optimization. The ability of smart meters to transmit this reading information in different starting times

enables an intensive enhancement for the end-to-end delay, offers faster reading, and avoid delays by considering that latency enhancement can be achieved using the network layer solution like RPL routing protocol. The system performance can be improved in different aspects by manipulating different routing metrics such as ETX, delay, hop count, and energy and their corresponding weight. However, the asynchronous transmission algorithm is considered a contribution for further system enhancement on top of the routing solution.

4.2 Proposed algorithms

4.2.1 The rationale for proposing new algorithms

The main reason to introduce new algorithms for data packet transmission is to enhance the system's end-to-end delay performance further. The latency improvement is based on controlling the starting time of data packet transmission that ensures less collision with other nodes' packets. The algorithms' results are compared with both the synchronous and random asynchronous data transmission cases. Because asynchronous transmission always outperforms synchronized transmissions, it is important to propose automated asynchronous criteria that show greater results than the randomized case. The realistic scenario of smart metering applications usually supports individual configuration of each smart meter in the network. Hence, we can exploit this option to adjust the beginning sending time of each node's UDP packet and mitigate the network congestion.

4.2.2 Algorithm 1

This algorithm aims to classify nodes according to their given synchronized end-to-end delay. The nodes with the highest delay will then be assigned enough time guard before and after their data packet transmission. However, the nodes with lower delay will be sent asynchronously with a time guard relative to their synchronous delay. In other words, the greater the nodes' end-to-end delay in the synchronous scenario, the more the guard

time band before and after the data packet transmission. This approach results in reduced node latency, as we will see later in the next results section.

Algorithm 1:

```

1 for Every node do
2   Classify into a delay category (high medium low)
   if  $E2Edelay > 200ms$  then
3     Set as high delay nodes

4    $100ms < E2Edelay < 200ms$ 
   Set as medium delay nodes

5    $E2Edelay < 100ms$ 
   Set as low delay nodes
   for Each delay category do
6     Add enough time guard before and after high delay nodes.
     Allow asynchronized transmission of the remaining nodes

```

4.2.3 Algorithm 2

The network nodes go through two main filtration steps. The first is the delay classification, in which the nodes are divided into high, medium, and low delay nodes. The latency statistics are given from the synchronous scenario. The second filtration is to group nodes according to their common forwarding nodes (CFNs).

The routing table or DODAG topology constructed through the synchronous transfer of UDP packets is used to realize and divide the nodes according to their forwarding nodes. The nodes with the same preferred parent are assigned to a single group. The high-delay nodes will be assigned a suitable guard time before and after transmission. Also, enough time separation will be assigned to nodes with CFN. However, nodes without CFN will allow synchronous transmission of their data packets. This is because these nodes will never collide with each other, and the interference is unlikely to occur.

Algorithm 2:

```

1 for Every node do
2   Classify into a delay category (high medium low)
   if  $E2Edelay > 200ms$  then
3     Set as high delay nodes

4    $100ms < E2Edelay < 200ms$ 
   Set as medium delay nodes

5    $E2Edelay < 100ms$ 
   Set as low delay nodes
6 for Each delay category do
7   Filter the nodes with Common Forwarding Node (CFN)
   Add enough time guard before and after high delay nodes
   Allow transmission for nodes with CFN according to their
   synchronous delay.
   Allow synchronized transmission of nodes without CFN.

```

4.3 Comparison between RF and PLC

A comparison is conducted between wireless RF and PLC PRIME networks separately in terms of nodes' end-to-end delay using both algorithms. Results show that the delay can be reduced for all network nodes below the predefined threshold by using just a single RPL routing metric (ETX).

4.3.1 Wireless RF network

For the realistic wireless RF network located in El Minya, the smart meters are simulated using the Whitefield simulation environment. The nodes are inserted in the same location as the realistic scenario. A suitable link failure or path loss model is used with a path loss exponent of 5.7 as to emulate the realistic attenuation and the existence of obstacles and buildings. The links between nodes are assumed to be asymmetric such that the RSSI is the same for any two end-devices.

The smart meters are emulated with sky motes with a compatible cc2420 radio chip. This driver functions as the alternative for the actual cc1312 chip and offers a transmission power range between -10 dBm to 0 dBm.

For radio duty cycling (RDC), CONTIKI-MAC is used along with a channel sense rate of 8 Hz as the main nodes' configuration. The user data-gram protocol (UDP) data packets are sent at a rate of 30 seconds to the sink node with a size of 127 bytes in order to conform with the 6LowPAN standard. Although reading data's realistic traffic rate is repeated every 12 hours or twice a day, this rate is not applied to the Whitefield simulation environment to save too much simulation time. Hence, the results can be reliable because it will give a good insight for longer traffic interval. The radio links are assumed to be asymmetric, and the transmission power is configurable on each node separately. The transmission power is adjustable on a node basis, and it is commonly adjusted to 0 dBm.

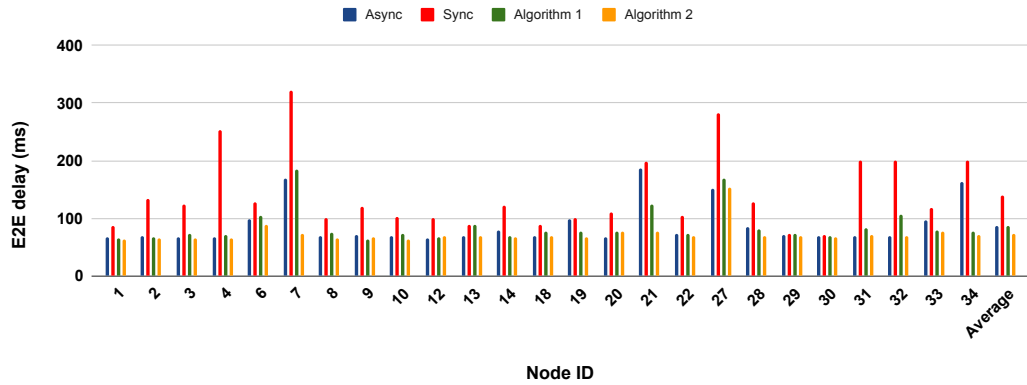


FIGURE 4.1: End-to-end delay comparison for RF network between synchronous, random asynchronous, and both algorithms

Fig. 4.1 shows the end-to-end delay of the RF nodes for different synchronization algorithms. ETX is used as a single routing RPL metric, and it is selected to offer better latency results as it is considered the best candidate for link reliability and congestion mitigation. Other routing metrics may also be considered for other system requirements like energy consumption and network lifetime. Whitefield environment support all Contiki RPL routing metrics under minimum rank with hysteresis objective function. It supports hop count, delay, and energy metrics. Also, the objective function

may be modified for better performance results. However, for our case, which requires a minimum end-to-end delay, it is preferred to use the expected transmission count for path costs. The value of ETX is updated with each DIO message broadcast between nodes and updated for nodes' routing table.

On top of the routing solution to improve the delay, the previously mentioned composite RPL metric is excluded, and the asynchronous algorithms are the alternative. This idea's emergence stems from the fact that most smart meters in the real scenario can be controlled through its starting transmission time of data packets. In other words, the beginning of UDP data transmission is adjustable through all smart meters in the network. That's why it is beneficial to further exploit such a feature to further enhance network performance, especially in terms of delay and energy consumption. The smart meters in the real scenario includes gas and water meters as well as electric meters for aggregation and collection of readings. A predefined E2E delay of 200 milliseconds is needed on a node basis. Both synchronous and asynchronous delay statistics are used to compare for new defined algorithms 1 and 2. The main goal is to achieve better delay results than the random asynchronous case.

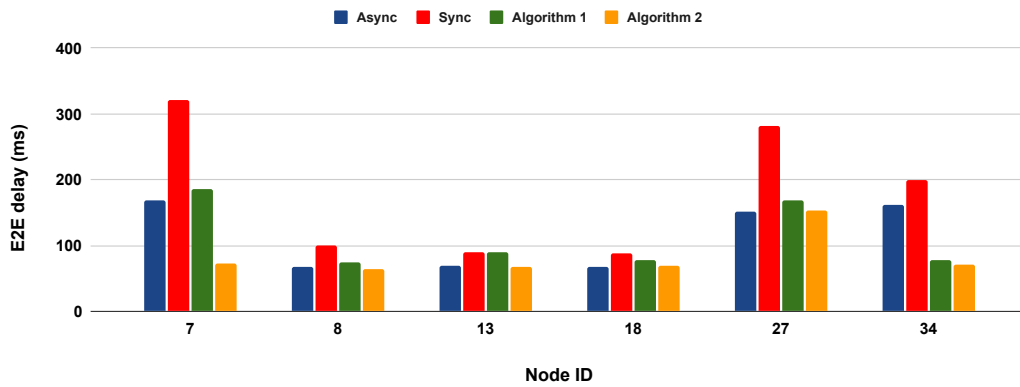


FIGURE 4.2: E2E delay performance comparison for some RF network nodes

Algorithm 1 shows better delay results for some nodes and worse latency performance for others. Nevertheless, the whole system's average net delay is almost the same as the random asynchronous case, with all nodes having a delay below the prespecified threshold. As we can see in the figure above, the end-to-end delay is improved. The used algorithm 2 succeeded in achieving the predefined latency requirement without the use of the composite additive RPL metric. Therefore, algorithm 2 demonstrates improved overall latency performance with the best system averaged delay.

For future insights, the transmission of UDP data packets can be managed automatically and in dynamic behavior. This necessitates a periodic broadcast of synchronous end to end delay through the whole network. This information may be included in the control messages, which enables dividing nodes into three delay categories; high, medium, and low. Moreover, each node can configure itself for an instant time for transmission. In order to save power consumption of the network, the smart meters may enter the sleep mode during the idle state while maintaining the bidirectional communication of broadcast messages like DIO and keep alive. This will ensure that all nodes in the network are joined and synchronized to the DODAG and keep multi-hopping efficient.

4.3.2 PRIME PLC network

For the realistic PRIME PLC network located in El-Minya, the smart meters are simulated using the Whitefield simulation environment. Two types of cables are mainly used to emulate the real power line communication, underground and overhead cables. The cables are mainly characterized by their transmission and reception interface impedance and attenuation and interference.

A suitable transmission power spectral density (PSD) is used for the simulation that conforms with the PRIME PLC standard. The current number of repeaters are actually inserted into the simulation environment to test

the coverage, delay, and energy performance. The default topology formation in PRIME takes place in the MAC layer using layer 2 routing. The topology construction is based on the shortest path algorithm at which the DCU is considered the base node (BN) and others are service nodes (SN). However, this routing construction is exchanged with the RPL routing protocol in layer 3 (network layer). In other words, PRIME MAC L2 routing is exchanged with RPL routing protocol. The front end of PLC nodes is modified such that it interprets and understands radio frequency wireless communication. An interface of cc2420 driver is used to do this task.

This is to give insight into future adoption and adaptation of G3 PLC standard, enabling RPL in its stack. To have a good insight into future hybrid solution, it is important to study RF and PLC's performance separately and then apply the combined network accordingly. CONTIKI-MAC is the layer employed for duty cycling of radio channels with a configurable link check rate of 8 Hz. The User Data-gram Protocol (UDP) is managed by the transport layer in which the data packet transmission rate is set to 30 seconds. The packet size is adjusted to 127 bytes, which is the maximum length for the 6LowPAN standard.

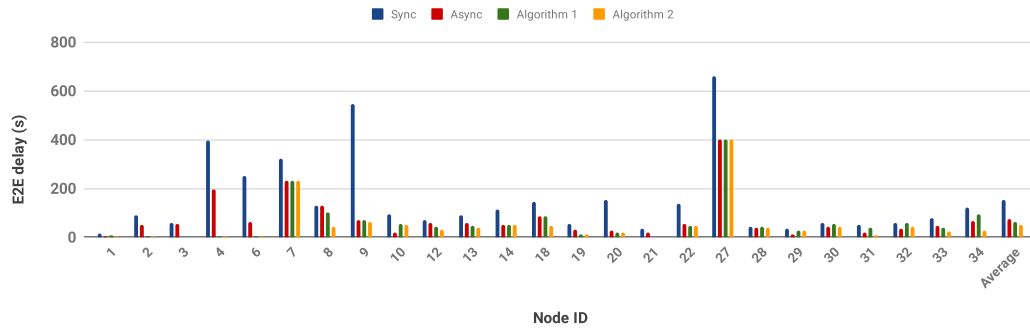


FIGURE 4.3: End-to-end delay comparison for PLC network between synchronous, random asynchronous, and both algorithms

The UDP packets are mainly unicasted from each node to the destined root by defining the client and server port numbers. The sink or DCU, in turn, waits for packets from smart meters, receives, and finally prints them. As seen in Fig. 4.3, the PRIME PLC network's end-to-end delay shows

TABLE 4.1: Simulation parameters

Parameters	Value
Simulation tool	Whitefield environment
PHY and MAC layer	IEEE 802.15.4
Network layer	RPL
Adaption layer	6LowPAN
Objective function	MRHOF with ETX metric
Transmission PSD	-50 dBm/Hz
Data rate	250 Kbps
Data rate transfer	127 byte payload every 30 seconds

worse than its wireless RF counterpart.

For the current PRIME model applied in the Whitefield, we should consider that RPL shows poor delay results when applied to the whole network framework. Consequently, RPL is applied and implemented to different individual sections in the PRIME network. Hence, we have multiple sectors of smart meters configured by RPL such that the UDP sink server is common among all sectors. The repeaters are inserted in the same location as the realistic scenario to ensure 100 % area of signal coverage.

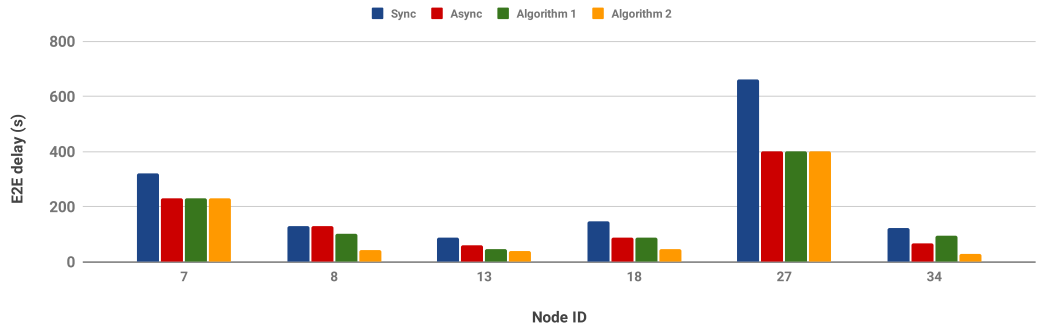


FIGURE 4.4: E2E delay performance comparison for some PLC network nodes

In fact, node 27 is the farthest meter from the root or data concentrator unit. This is the main reason for its high delay performance. Node 7, however, uses multiple hops to reach the sink destination. Generally, two cables are used to emulate the realistic scenario, the underground and overhead cables. Generally, the overhead cables show high signal attenuation, which is greater than the one of the underground cables. This is mainly due to the path loss in the air beside the existence of obstacles and buildings that may cause interference and signal reflection.

4.3.3 RF against PLC performance

It should be noted that the delay curve for RF is plotted with milliseconds, whereas the PRIME PLC curve reveals delay calculated in seconds. This study confirms that wireless RF under RPL and asynchronous transmission outperforms the PRIME PLC network with the same configuration. This may give an insight for future adaptation to the hybrid model that most of the RF links may be selected instead of the PLC links to achieve such delay predefined requirements. For the general case, each node may have an equal probability of choosing either RF or PLC according to the configured path cost or routing metric and its relation to the system requirements. For example, if the major system requirement is to minimize the delay for E2E communication, the technology with lower delay cost will be selected. Similarly, if the main network concern is link reliability and higher PDR, then the PLC technology will mostly be chosen.

Finally, a suitable automated and dynamically adjusted transmission mechanism can be used to ensure successful packet reception for all nodes without causing interference or congestion in the whole network. This can be achieved through machine learning algorithms that need plenty of historical data of the network performance and offer a near-accurate model for the network. The last approach may optimize the overall system energy consumption and increase the nodes' lifetime through precise and dynamic power configuration.

Chapter 5

Conclusions and Future Work

5.1 Conclusions

In this work, we introduced a new RPL routing metric DA-RPL to reduce the nodes' end-to-end delay below a specified threshold by selecting paths with less latency and reduced congestion. Extra nodes were inserted as repeaters to contribute to latency reduction and to reduce the congestion at concentrated nodes. The results reveal that all system nodes met the predefined requirement and with less consumed energy. To generalize for different network environments, the coefficients of the metric can be manipulated dynamically with the changes in the network to optimize the system specifications.

Furthermore, the new proposed algorithms of asynchronous transmission combined with appropriate ordering show better network performance results in terms of end-to-end delay as well as consumed energy among nodes. The significant reduction in the nodes' latency is mainly due to efficient congestion in the whole network by avoiding packet collision. Results also confirmed that RF wireless network may reveal better performance than PRIME PLC network, specially if the attenuation and obstacles between nodes are not high relative to the transmission power.

5.2 Future directions

For future work, appropriate automated transmission power mechanism beside the composite metric can be used to provide better congestion mitigation and offer a promising enhancement in the network performance in terms of delay and energy consumption. Furthermore, a wired PLC network can be combined with a wireless system and a modified RPL with a hybrid metric can be used to enhance the system performance.

Several research studies are done on hybrid modeling in order to implement it in the realistic case. An adaptation to the G3-standard can emerge the possibility for hybrid routing under RPL umbrella by using the network layer of the G3-PLC. Furthermore, the new wireless technology, Wi-SUN, can utilize its RPL protocol in its stack to integrate with G3 stack. The hybrid routing metric can be identified independently on each of the two technologies according to its requirements and challenges with its links. There are three different proposed methods that can be used to integrate both wireless and wired technologies under RPL routing. All of them assumes that all nodes should have two interfaces; one for RF (802.15.4) and one for PLC (PRIME).

The first method is called Multiple RPL Instances (MI) that aims to use two RPL instances one per technology. For each node interface, specific objective function OF, and instance id are identified. Hence, the net is two constructed DODAGs rooted to a single sink node. The primary technology is assigned a lower RPL instance ID, whereas the backup technology is defined by a higher instance ID. An appropriate switching between the two interfaces occurs upon failure. Since RPL only enables transition to a higher instance ID, the backup possibility is not high. However, MI method can be easily implemented and offers high stability to the network. In order to have more advantage from the multiple interface feature, the limitation on switching between different instances should be altered. The new proposed concept should take into consideration the looping issue as well as the number of switches between interfaces or technologies. It may enable the nodes

to access or join more than one instance to reach its sink node through varieties of selected routes' choices. According to the predefined system requirements, the route metrics, and the link capacity, each node should be able to choose the optimum instance for forwarding its data packets to the root.

For far future, it is important to take into account the long range solution in the hybrid wireless and PLC network despite its restricted bandwidth. The multiple interface management can be controlled through using an algorithm that allows direct link from smart meter to the sink node. This dedicated link should indicate long distance communication with new adaptations to the routing protocol with a specific routing metric. This mechanism is expected to offer availability for critical packet transmission with lowest delays.

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